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Indoor Localization based on Multiple LEDs Position Estimation

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Abstract—This paper describes the simulation results and hardware implementation of an inexpensive, low-complexity LED based indoor positioning system. Localization by multiple LEDs estimation model (MLEM) approximates position of a mobile receiver by the acquisition of positional information from LED transmitters. Multiple LED orientation can either be with or without overlap. Receivers in a no-overlap LED orientation experience only single access while multiple access receivers are designed for orientations with overlaps. Single and multiple access systems were developed and implemented by the use of low cost ATMEG 328 microcontroller. Since multiple LEDs transmit data at the same wavelength and are asynchronous, overlap in multiple access system causes interference. The possibility of this interference is reduced by packet based pulse duration multiplexing (PDM) and a low duty cycle transmission protocol. By the use of MLEM, root mean square error in position estimation is reduced to about 1 percent of the length an indoor location. Experimental results show that overlap increases positional accuracy over a wider coverage region and that the multiple access system allows for a more reliable positioning.

Keywords— Indoor localization; optical wireless communications; Multiple LEDs; Microcontroller-based positioning; Overlap

I. INTRODUCTION

Indoor positioning and tracking has been the subject of exploration in a number of recent publications [1]. This is due to its applicability in various areas of life which include security, medicine, emergency rescue, object localization and tracking, system delivery, indoor mapping and trajectory generation [2]. Various methods for indoor positioning that have been investigated include object localization by the use of global positioning systems (GPS), radio frequency identification (RFID), ultrasound, infrared and wireless local area networks (WLAN). GPS has been used extensively for accurate positioning outdoors but, due to severe signal attenuation by walls and other obstacles, GPS signals greatly suffer degradation in indoor environments and hence are not effective for use in indoor tracking systems [1]. Indoor localization by ultrasound, WLAN, and RFID require additional infrastructure to operate [3].

Recently, with the current rise in Light Emitting Diodes (LEDs) as an effective method for lighting [4], LED based indoor positioning systems have been studied as a viable alternative to other aforementioned methods. This is because LED positioning has higher accuracy, no electromagnetic interference, higher security and higher capacity for data transmission [5], [6].

LED based positioning involves the use of known coordinates of LED transmitters to derive the unknown coordinates of an optical receiver which is usually a photo-detector (PD). The PD is used to acquire and translate information sent from LEDs. The acquired data is then analysed by appropriate algorithms to define the position of the receiver. The process is illustrated in Fig. 1. The sent signals from the LEDs however, suffer from a number of distortive effects which include multipath propagation, noise, shadowing and interference from other LED sources [7]. These distortive effects have posed challenges to developing a system for indoor positioning. Thus, a number of researchers have recently developed various algorithms to mitigate these effects.

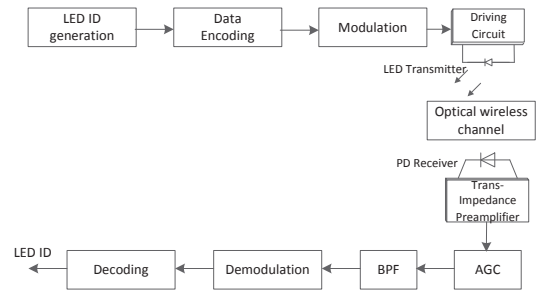


Fig. 1. Optical link design for a single transmitter and single receiver link. AGC: Automatic Gain Control; BPF: Band Pass Filter

Most of the papers published so far have explored methods that are based on received signal strength (RSS), angle of arrival (AOA) [1], time based multiplexing, frequency based multiplexing [8], receiver orientation modification [9], code division multiple access [10], and multiple optical receivers

[11]. In addition, current trends have investigated LED based indoor positioning by RF carrier allocation [12], the use of smartphones [13], and location fingerprinting [14]. Heading estimation by the use of smartphone uses accelerometers, magnetometers and gyroscopes to track the movement of a receiver indoor by approximating the motion profile of the receiver module. This method is still being improved for real life scenarios while tracking by location fingerprinting requires complex algorithms. RSS and AOA methods have attempted to imitate successes in GPS systems by the use of trilateration and/or triangularization. These methods have been simulated to perform well. However, it is assumed that optical power from one source can be sufficiently separated from that of another source and that the received power, proportional to luminous intensity shown in Fig. 2a, is unique to a specific point. Nevertheless, the received power from an LED is not unique to a particular point but is rather the same for an infinite number of points on any contour as shown in Fig. 2b. To simplify designs with these algorithms, specific heights or angles are assumed in their simulation but a practical mobile receiver is not constrained by a particular height or angle [12], [9]. These assumptions make it difficult to implement the algorithms in practice and when implemented, the algorithms are complex and either expensive to implement or computationally intensive. Hence there is need to design a simple LED based positioning system which operates in real life scenario.

In this paper, we take advantage of interfering light beams to improve the accuracy of a LED based positioning system. We investigate possible position estimation error and examine various access systems perceivable by the receiver module. By using realistic assumptions, we develop a prototype from inexpensive off the shelf components.

The rest of the paper is organized as follows: description of the proposed positioning model is presented in Section II. In Section II-A and II-B, various configurations for the system design are discussed. Experimental findings and discussion on the performance of the proposed system are given in Section III. Finally, conclusions are presented in Section IV.

II. MULTIPLE LED ESTIMATION MODEL (MLEM)

MLEM uses both the content and pattern of reception of data carrying packets from single or multiple LEDs to directly infer the position of the receiver. Photons from an LED source travel with an irradiation angle which determines the spread of the beam from the source. This spread is used to arrange the LEDs so that irradiation from the source allows possibility of overlap with nearest neighbours. To infer position, a receiver in a position $x(t)$ at a time t identifies specifically which optical transmitter(s) are in the region of reception of the receiver module. If at the time t_1 , the receiver is in a region of no overlap and receives data from the transmitter at (x_{t_1}, y_{t_1}) , the receiver is said to be at the point (x_{t_1}, y_{t_1}) . Based on this, by the use of multiple LEDs, the receiver identifies multiple locations. The proposition of this model is that the smaller the distance between LED sources, the lower will be the

positioning error. We investigate the viability of this model under various configurations as explained in Section II-A and II-B. By this method, the only condition for positioning is whether or not the signal from the LED, is received.

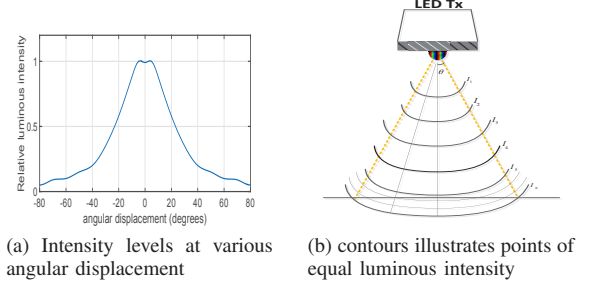


Fig. 2. Optical transmitter (LED) propagation characteristics. Source: [15], [16]

If this signal is not received, then the user is definitely in a non-coverage region. The non-coverage region is a region not covered by the modulated signal used for positioning. For a long, narrow area such as a hallway or a passage, Fig. 3 shows three possible scenarios between the light beams. For this work, a beam is the light coverage region where the LED light is above a detectable level.

Real life observations and practical light designs ensure that there are no non-coverage regions in indoor lighting. Consequently, in indoor positioning by MLEM, the mobile receiver is either at a location where there is no overlap between data packets or in a location where there is overlap as illustrated in Fig. 3a and 3b respectively. These two conditions are considered as single access (no overlap) systems and multiple access (overlapping) systems. MLEM receivers are designed and investigated to determine positioning accuracy of the model as subsequently presented.

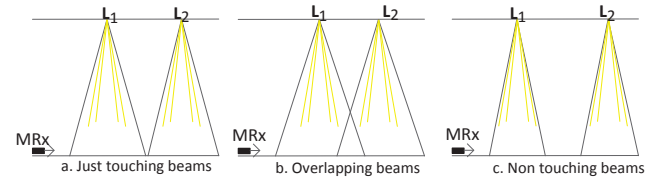


Fig. 3. Possible interaction between light beams from similar LED sources. MR_x : Mobile receiver, L_1 : First LED source, L_2 : Second LED source.

A. Single Access System

The single access system is setup to investigate the feasibility of a low-cost LED-based indoor positioning system. The optical channel considered in this work is the line-of-sight (LOS) links. Single-access in this context means receiving position information from either of two LEDs with non-overlapping beam of light. Each LED transmits a unique 8-bit code which contains its coordinates. The LEDs is designed to transmit this position information modulated using Pulse Amplitude Modulation (PAM) format to keep the algorithm

simple. Thus, the radiated optical signal is linearly proportional to the amplitude of the electrical signal. To estimate the unknown position of the receiver, the received optical signal is converted back to proportionate electrical signal by the photodetector. The logical 0s and 1s of the 8-bits unique code are determined based on the received signal amplitude at each bit period. Thereafter, the receiver compares the estimate of the unique code with the known codes in its database in order to decipher the current position in real time.

For a channel with impulse response $h(t)$, the received optical data is converted to a proportionate current by the photodiode. This current signal $y(t)$ based on the modulated optical signal $x(t)$ is given in [5] by

$$y(t) = Rx(t) \otimes h(t) + N(t) \quad (1)$$

where R is the responsivity of the photodetector, $N(t)$ is the noise function, and \otimes denotes convolution.

B. Multiple Access System

Data transmission via PAM suffices for the single access system. However, in the overlap region, since all transmitters are designed to transmit at the same wavelength, at the same time and in the same space, interference may occur. The interference in this region could either be from other LEDs, from ambient light or stray radiation from a similar device. Positional information to the LED is encoded using pulse duration multiplexing (PDM) to reduce possibility of interference by ambient light and stray devices. Encoding by PDM represents 1s and 0s by altering the duration of a pulse. This encoded data is modulated to a higher frequency using on-off keying (OOK) modulation. The high frequency (modulated) signal is transmitted through individual LED transmitters. If the signal transmitted from LED L_1 is $x_1(t)$ and $x_2(t)$ from LED L_2 , the received current signal $y(t)$ is given by

$$y(t) = R(x_1(t) \otimes h_1(t) + x_2(t) \otimes h_2(t)) + N(t) \quad (2)$$

where $h_1(t)$ and $h_2(t)$ are the channel response from L_1 and L_2 respectively. Asynchronous data transmission is used to keep MLEM simple and inexpensive. Hence there is possibility of interference between bits of different transmitters. To reduce this interference, the modulated data are transmitted in short packets. This packet embeds the LED ID in a packet consisting of start bits, encoded data bits and a stop bit as shown in Fig. 4.

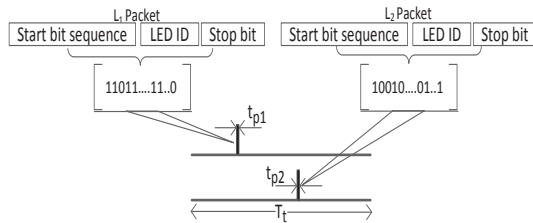


Fig. 4. Illustration of data packets formation and low duty cycle to reduce probability of collision.

The code packet for each LED transmitter is sent in a short pulse. The receiver recognises the start bit sequence in the packet and starts decoding. For a scenario with possibility of overlap between two LEDs, illustrated in Fig. 4, the duration of the pulse is given by t_{p1} for the first LED transmitter L_1 and t_{p2} for the second LED transmitter L_2 . The total period for transmitting a sequence of code is given by T_t . The packet is transmitted with a low duty cycle (t_{p1} and t_{p2} is far less than T_t) to reduce collision with packets from other LED transmitters. For L_1 , the packet duty cycle DC_1 is given by the fraction $DC_1 = \frac{t_{p1}}{T_t}$.

For a duty cycle $DC_1 = DC_2 = \frac{1}{N} \quad \forall N \geq 2$, the probability of collision P_c of packets from L_1 by those from L_2 is the probability of packets from the L_2 being in the region of the packets from L_1 as the same time. This is mathematically illustrated as:

$$P_c = N \int_0^{\frac{1}{N}} f_{p1}(x) dx \int_{\frac{1}{N}}^1 f_{p2}(x) dx, \quad (3)$$

where $f_{p1}(x)$ and $f_{p2}(x)$ represents the rectangular pulses from L_1 and L_2 respectively. For normalized pulse amplitudes, (3) reduces to

$$P_c = \frac{2}{N}. \quad (4)$$

In our design packet sizes and period were kept constant and the duty cycle ratio was kept at about 0.1. The probability of collision is therefore given by $P_c = 0.2$. Consequently, the probability of collision of packets from two LED sources is reduced to 2 out of every 10 packets transmitted.

III. RESULTS AND DISCUSSIONS

In this section, we present results obtained via simulation using MATLAB® communications toolbox and hardware implementation of the LED-based indoor localization system. Simulation is used to compare the positioning error in single access and multiple access systems. To quantify the results, we used the normalized Root Mean Squared Error (RMSE) metrics given by:

$$R = \frac{\sqrt{\frac{1}{n} \sum_{i=1}^n (x_t^{(i)} - x_p)^2}}{L}, \quad (5)$$

where L is the total distance covered by light from LEDs, n is the number of iterative points, $x_t^{(i)}$ is the true location of the receiver at any iterative point i and x_p is the location of the transmitter which represents the estimated position of the receiver. The optimal design conditions obtained from the simulations are implemented in hardware and performance of the system with overlapping and non-overlapping beams evaluated.

A. Simulation Results and discussions

The systems under consideration here are shown in Fig. 3a (Case 1) and 3b (Case 2). For Case 1, a mobile receiver is placed at a point in the coverage region and moved in small discrete intervals. Positioning error is calculated as the deviation of the ascribed receiver location (the LED

coordinates received) from the true location of the receiver. The RMSE is obtained using (5). The process is repeated for increasing number of LEDs and the results are shown in Fig. 5. For Case 2, the distance between the LEDs determined the level of overlap at the receiver. The effect of the level of overlap on the positioning error is carried out by varying the distance between LEDs, thereby causing overlaps, and measuring the error. It is observed that minimum positioning error occurred when the distance of overlap is equal to the distance of no overlap. Using this condition, positioning error is calculated by a similar process as described in Case 1 and results presented in Fig. 5. These two systems are compared and the positioning error for both is seen to reduce as the number of LEDs increases. It is observed that by the use of MLEM, with 10 LEDs, the positioning error can be reduced to 2.63% of the total length of the passage for just touching beams and 1.05% of the length of the passage for overlapping beams. Generally, by the effective use of overlap in Case 2, the error in positioning is reduced by about 50% and better accuracy figures could be obtained by increasing the number of LEDs used.

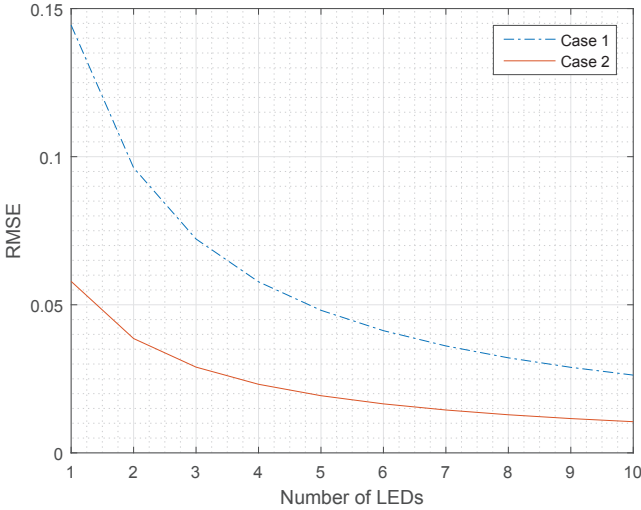


Fig. 5. Variation of RMSE vs Number of LEDs for Case 1 and Case 2. Case 1: Just touching beams (Fig. 3a) and, Case 2: Overlapping beams (Fig. 3b)

B. Experimental Results and discussions

For laboratory experiments single and multiple access systems are developed using ATMEG 328 microcontrollers and positioned as shown in Fig. 3. Height, which is the vertical distance between the plane of the LEDs and the plane of the mobile receiver, is kept at 30 cm due to workbench space constraint but the developed hardware has been tested to deliver data at a height of about 4 m. Other hardware specifications for the experiments are given in Table I. Results from the experiment are quantified by measuring the Packet Delivery Ratio (PDR) given by:

$$PDR = \frac{Pk_r}{Pk_s} \quad (6)$$

where Pk_r is the number of packets received correctly and Pk_s is the number of packets sent. For a single access system, Fig. 6 shows the variation of PDR with angular displacement as the mobile receiver travels on a particular horizontal plane parallel to the plane of the LEDs as illustrated in Fig. 3. As expected, full packet delivery is obtained at the perpendicular from the LED to the horizontal plane and a region at angular displacement of $\pm 5^\circ$ to this perpendicular.

TABLE I
PARAMETERS FOR EXPERIMENTAL SETUP

Parameters	
Light emitting diode (LED)	OSRAM IR LED (SFH 4550)
angle of half intensity $\varphi_{1/2}$	$\pm 3^\circ$
peak wavelength λ_p	860 nm
total radiant flux ϕ_a	70 mW
rise and fall time t_r, t_f	12 ns
Photodetector (PD)	VISHAY (TSOP 38238)
Directivity (θ)	45°
Peak wavelength λ_p	950 nm
Minimum irradiance $E_{(emin)}$	0.12 mW/m ²
Microcontroller	ATMEG 328
Clock frequency	16 MHz

As the receiver moves away from this region, the PDR reduces. Furthermore, decrease in the distance between the plane of the LED and the receiver shows full packet delivery at a wider angular displacement of $\pm 20^\circ$ from the perpendicular. Therefore the region of reception of packets is affected by the distance between the transmitter and receiver plane. The larger the distance, the narrower the region of reception and this narrow region implies greater positioning accuracy (Section II). Thus MLEM does not assume a fixed height but, provided the receiver is in the region of coverage, the positioning accuracy is improved as the vertical distance between the transmitter and the receiver increases.

To determine the effect of overlap on position error, the transmitters, receiver system was arranged based on the angle of coverage of the transmitters given in Table I and the condition for minimal error in overlap (Section III-A). We measure the variation of PDR with linear displacement on the receiver horizontal plane for both single and multiple access system and the results are presented in Fig. 7 and 8 respectively.

The hardware is designed to send packets every 200 ms. Hence for successful packet delivery every seconds a minimum of 1 out of every 5 packets sent must be correctly decoded. Thus a PDR above 0.2 is required. In Fig. 7 there is a region of no coverage (PDR below 0.2) between the two LEDs hence the position of a receiver in this region is unknown. This situation is taken care of by the overlap design shown in Fig. 8 where the PDR is almost above average (0.5) in all the region of coverage. Packet reception occurs for 66.6% of displacement in the single access and for 86.6% in the multiple access system. It is observed that packet loss, given by low PDR,

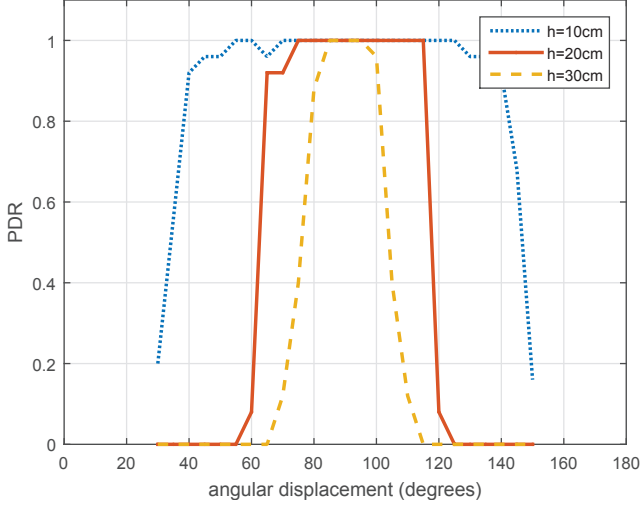


Fig. 6. Variation of PDR with angular displacement of receiver at various distances from a transmitter.

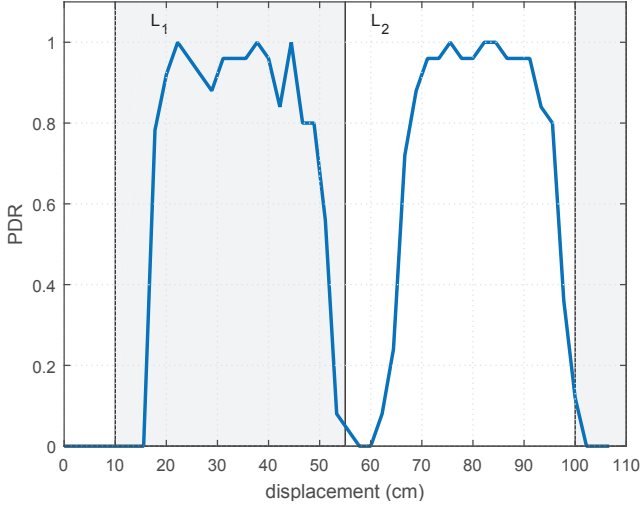


Fig. 7. Variation of PDR with displacement for single access system of two LEDs L_1 :coverage region for LED 1 and L_2 : coverage region for LED 2.

happens more just at the boundaries near the overlaps (Fig. 8) where the receiver has to distinguish between being in a region of overlap or not. By (5), the RMSE value for the system with overlap is calculated to be 0.069 while the non overlapping system has an RMSE of 0.12. These RMSE values are slightly more when compared to the simulation based RMSE values for two LEDs because ideal conditions are assumed in simulation.

In addition, it is also observed that the single access system identifies just two positions (L_1 and L_2) for two LEDs, whereas the multiple access systems identifies an extra 'overlap' region. As the number of LEDs increases, the multiple access system identifies more overlapping regions and thereby improves the accuracy of positioning. Thus, MLEM takes advantage of overlap to improve the reliability of the system by offering a better resolution of positioning, better coverage and lower RMSE.

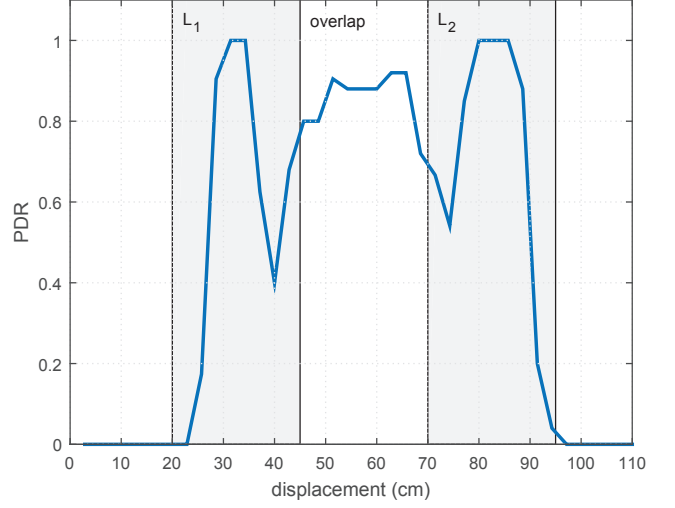


Fig. 8. Variation of PDR with displacement for multiple access system of two LEDs (overlap). L_1 :coverage region for LED 1 and L_2 : coverage region for LED 2. overlap indicates the overlap region between L_1 and L_2 .

IV. CONCLUSION

In this paper, a microcontroller-based LED indoor positioning system using MLEM is described. The system is designed to be compact and inexpensive by the use of simple positioning algorithm. The paper determines RMSE values for an indoor location using MLEM in both single access and multiple access LED transmitter configurations. By the use of pulse duration multiplexing to reduce interference, the paper demonstrates how optical signals can be transmitted in the same frequency, space and time. Therefore, overlap which should normally cause packet loss is used to improve the reliability of positioning and reduce positioning error thus making the system more accurate and applicable to real life situations. Data packets carrying transmitter coordinates are correctly decoded at the receiver irrespective of whether there is overlap or not.

In future works, the applicability of this positioning technique to more general scenarios would be investigated and a detailed research of multipath reflections on signal decoding will be considered.

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